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Performance analysis of a new radial-axial flux machine with SMC cores and ferrite magnets

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Soft magnetic composite (SMC) is a popular material in designing of new 3D flux electrical machines nowadays for it has the merits of isotropic magnetic characteristic, low eddy current loss and high design flexibility over the electric steel. The axial flux machine (AFM) with the extended stator tooth tip both in the radial and circumferential direction is a good example, which has been investigated in the last years. Based on the 3D flux AFM and radial flux machine, this paper proposes a new radial-axial flux machine (RAFM) with SMC cores and ferrite magnets, which has very high torque density though the low cost low magnetic energy ferrite magnet is utilized. Moreover, the cost of RAFM is quite low since the manufacturing cost can be reduced by using the SMC cores and the material cost will be decreased due to the adoption of the ferrite magnets. The 3D finite element method (FEM) is used to calculate the magnetic flux density distribution and electromagnetic parameters. For the core loss calculation, the rotational core loss computation method is used based on the experiment results from previous 3D magnetic tester. [http://dx.doi.org/10.1063/1.4973206]

I. INTRODUCTION

Due to the unique properties of soft magnetic composite (SMC) materials, such as the isotropic magnetic and thermal characteristic and low eddy current loss, various kinds of 3D flux electromagnetic devices has been proposed and investigated in the past years, including the transverse flux machine, and the radial flux machine with the extended stator tooth tip in the axial direction and et al.[1–4] Moreover, the magnetic characteristic measurement and modeling of SMC material,[5,6] new design optimization method for the SMC machines,[7] and new electrical machine with SMC cores are the hot research topics as well.[8,9]

Compared with the electrical machine made by electrical steel, SMC machine can't be regarded as the high performance machine.[10,11] However, the SMC machine has the potential for the low cost applications, since the manufacturing cost of the SMC machine can be dramatically reduced if a high-productivity low-pressure press is used in the molding in the mass production.[4]

Ferrite magnets are usually used to design PM machines for low cost application as it is much cheaper than other PM materials. To improve the torque density of the PM machine with ferrite magnets, the flux concentrating structure is suggested to be utilized.[6] In this paper, a new radial-axial flux machine (RAFM) with SMC cores and ferrite magnet is proposed. Compared with the traditional PM machines with ferrite magnets where the spoke PM in the rotor[12] is adopted to concentrate the PM flux, the flux concentrating of the RAFM is resulted by the extended radial stator tooth tip and

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axial stator tooth tip. From viewpoint of the manufacturing, the RAFM is very easy. For the better understanding of the merit of the RAFM, an axial flux machine (AFM) with extended stator tooth tip both in the radial and circumferential direction is designed and chosen as the benchmark machine. For the core loss calculation, the rotational core loss calculation method is used based on the experiment results form a 3D magnetic tester developed by the University of Technology Sydney.[1]

II. TOPOLOGIES OF RAFM

Fig. 1(a) and (b) illustrate the mechanical structure of the AFM with the extended stator tooth tip both in the radial and circumferential direction and the new designed RAFM. Both of these machines are quite similar to the yokeless and segmented armature machine (YASA) AFM. The difference is that the AFM has the extended stator tooth tip in the radial and circumferential direction, while the RAFM has the radial flux stator tooth and axial flux tooth tip and its axial flux stator tooth tip is extended both in the radial and circumferential direction as well as the radial flux stator tooth tip extended in both the axial and circumferential direction. As the space in the radial direction is utilized, the more PM flux can be used in the RAFM and thus higher torque density can be achieved.

For a fair comparison, both of two machines are designed with the same outer dimensions and are optimized to achieve the maximum output torque density. The outer radius of the stator core of these machines is 80 mm, the axial length is 60 mm, and the inner radius is 40 mm. The thickness of PM is 5 mm, and the thickness of rotor back is 6 mm. For the stator cores in AFM and RAFM, the SOMALY 500$^{\mathrm{TM}}$ with the density of 7.32 g/cm^3 is used. The PM is the Y30 ferrite magnet, thus the eddy current loss in the PM can be ignored. The designed RAFM can deliver the rated power of 4400 W at the speed of 4000 rpm, which can be used in the micro electric vehicle application.

III. 3-D FINITE ELEMENT ANALYSIS

A. Magnetic field distribution

Fig. 1(c) and (d) illustrate the no load magnetic flux density distributions of the AFM and RAFM. It can be found that the flux densities on the stator tooth tip of both two machines are very high though the ferrite magnets are utilized.

B. Flux, inductance and cogging torque

Fig. 2(a) illustrates the no-load PM flux linkage per turn of the RAFM and AFM respectively. Similar to the magnetic field distribution, the PM flux linkage of the RAFM is higher than that of

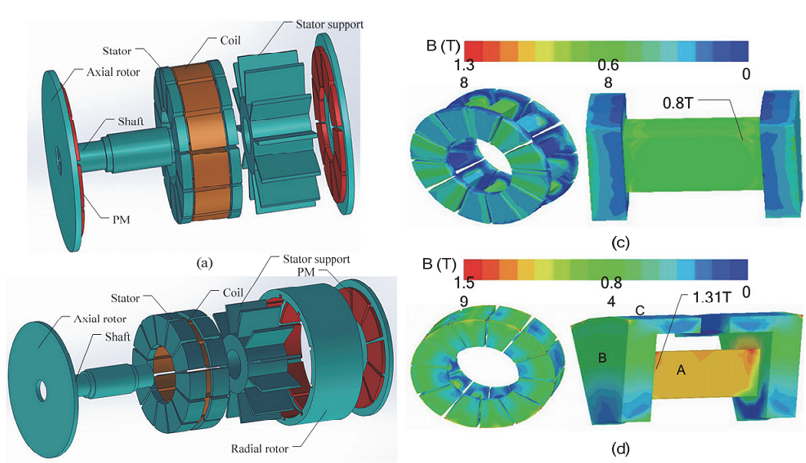

FIG. 1. (a) Mechanical structure of AFM, (b) Mechanical structure of RAFM, (c) Magnetic field distribution of AFM and (d) Magnetic field distribution of RAFM.

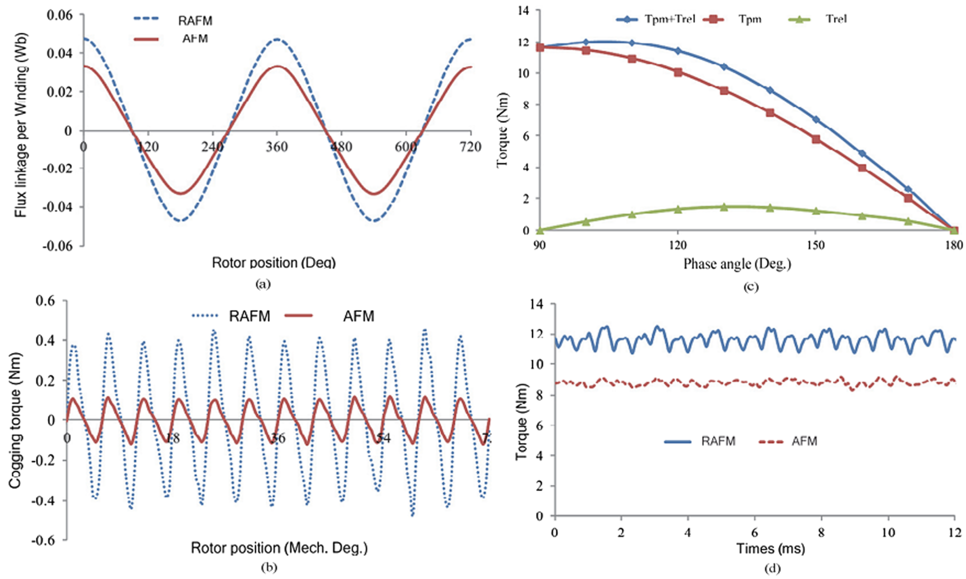

FIG. 2. (a) PM flux per winding of AFM and RAFM, (b) Cogging torque of AFM and RAFM, (c) Electromagnetic Torque of RAFM at the phase current of 36 A with the phase angle varied from 90 to 180deg, and (d) PM torque of RAFM and AFM.

AFM. The self inductance per turn of the RAFM and AFM is 1.527 mH and 1.633 mH respectively, thus the power factor of the new designed RAFM would be higher than that of AFM, which will benefit the choosing of cheaper driving circuit. Fig. 2(b) shows the cogging torque of AFM and RAFM.

To compressively understand the merits of the RAFM, the main parameters of the RAFM with only the axial flux PM, radial flux PM and both the axial and radial flux PM are compared in Table I. The inductance of RAFM is expressed as,

$$L = L_0 - L_m \cos(2p\theta_r) \tag{1}$$

where L_0 is the average inductance, L_m the peak value of the inductance ripple, p the number of pole pairs, and θ_r the mechanical angular displacement. As shown, both the radial PM and axial PM are contributed to produce PM flux linkage to the RAFM.

C. Electromagnetic torque

The electromagnetic torque of a PM machine is composed of the reluctance torque and the permanent magnet torque, it can be expressed as

$$T_e = \frac{m}{2}p\left[\frac{1}{2}(L_d - L_q)i_s\sin(2\beta) + \psi_{pm}i_s\sin(\beta)\right] \tag{2}$$

where m is the number of phases, L_d the d-axis inductance, L_q the q-axis inductance, i_s the stator phase current, β the phase angle between the phase current and back EMF, and Ψ_{pm} the PM flux linkage. Fig. 2(c) shows the electromagnetic torque of RAFM, it can be found that the reluctance torque can be ignored for the contribution of total electromagnetic torque if compared with the PM

TABLE I. Parameters Comparison of RAFMs.

	RAFM (Axial PM)	RAFM (Radial PM)	RAFM (Radial and Axial)
L_0 (mH)	1.58	1.60	1.53
L_m (mH)	0.02	0.03	0.20
PM flux per turn (mWb)	0.65	0.6	1.2
Cogging torque (Nm)	0.12	0.20	0.40

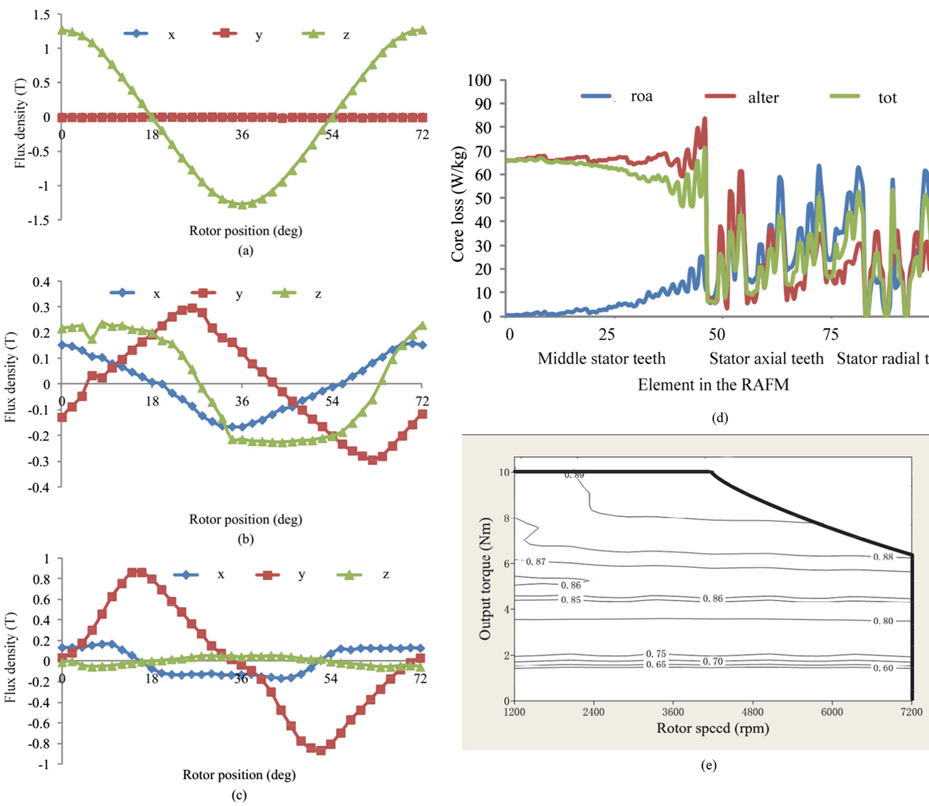

FIG. 3. (a), (b), (c) No-load B components in a typical element, (a) stator yoke (point A), (b) stator axial tooth (point B), and (c) stator radial tooth (point C), (d) Core loss components of total core loss of RAFM, and (e) Efficiency map of RAFM.

torque. Fig. 2(d) compares the waveforms of the PM torque of the AFM and RAFM at the phase current of 36 A. As shown, the average torque of the RAFM is higher than that of the AFM.

IV. CORE LOSS CALCULATION

In the designing of SMC machine the accurate calculation of core loss is very important, as the core loss in the SMC machine is the main loss. In our previous work, the rotational core loss is roughly two times higher than the alternating core loss, and it is the major part in the core loss of the 3D flux machine. Thus, in this paper, the rotational core loss calculation method is applied to calculate the core loss of RAFM. The formulations for calculation of the core loss of SMC can be summarized as below,

$$P_{core} = \sum_{e=1}^{Ne} \sum_{k=1}^{\infty} \left[P_{rk} R_{Bk} + (1 - R_{Bk})^2 P_{ak} \right] \tag{3}$$

$$P_{rk} = P_{hrk} + C_{er}(fB_{pk})2 + C_{ar}(fB_{pk})^{3/2} \tag{4}$$

$$\frac{P_{rk}}{f} = a_1 \left[\frac{1/s}{(a_2 + 1/s)^2 + a_3{}^2} - \frac{1/(2 - s)}{[a_2 + 1/(2 - s)]^2 + a_3{}^2} \right] \tag{5}$$

$$s = 1 - \frac{B_{pk}}{B_s} \sqrt{1 - \frac{1}{a_2{}^2 + a_3{}^2}} \tag{6}$$

$$P_a = c_{ha} f B_p{}^h + C_{ea}(fB_p)^2 + c_{aa}(fB_p)^{3/2} \tag{7}$$

where N_e is the number of element, P_{rk} the rotational core loss of *k-th* harmonics of B, R_{Bk} the axis ratio of *k-th* B harmonic, P_{ak} the alternating core loss of *k-th* harmonics, the detailed rotation core loss calculation can be found in Ref. 8.

By using the 3D FEM, the magnetic flux locus of the RAFM with the different rotor positions can be plotted. Three typical points of them are chosen to shown in Fig. 1(d). Point A is located in the middle of the stator tooth, point B locates on the stator axial tooth tip, and point C is located on the stator radial tooth tip, as shown in the Fig. 1(d). It can be found that the magnetic flux path on the middle of the stator tooth is the alternating one, the stator axial tooth tip and stator radial tooth tip are the elliptical one, as shown in Fig. 3(a), (b) and (c).

Based on the formulations of the rotational core loss calculation, the core loss density in the RAFM can be shown in Fig. 3(d), including the rotational core loss, alternating core loss and the total core loss components. The x-axis in the Fig. 3(d) is the element of the RAFM, it starts from the middle stator tooth (0 - 50) to the stator axial tooth tip (51 - 75) then the stator radial tooth tip (76 - 100). The y-axis in the Fig. 3(d) is the core loss density in the different elements. As shown, the core losses in the middle stator tooth is mainly dependent on the alternating loss, while rotational loss accounts for the majority of the losses in stator axial and stator radial tooth tips. The flux density in the stator middle tooth is much higher than that in the stator axial tooth tip and stator axial tooth tip, the total core loss density is high in the stator middle tooth.

V. PERFORMANCE CALCULATION

Efficiency map is very useful for valuing the performance of RAFM. To plot the efficiency map, the output torque and efficiency need to be obtained. The output torque of RAFM can be expressed as,

$$T_{out} = (P_{em} - P_{Core} - P_{pm} - P_{mech}) \Big/ \omega_r \tag{8}$$

where P_{em} is the electromagnetic power which can be obtained from multiplying the electromagnetic torque with the rotor speed, ω_r the rotor speed, P_{Core} the core loss, P_{pm} the magnet loss, and P_{mech} the mechanical loss. The magnet loss can be neglected, as the resistivity of the ferrite magnet is quite high. The mechanical loss is estimated as 1.5% of the total output power. The efficiency map of RAFM is shown in Fig. 3(e). It should be noted that the d-axis current equals 0, though the flux weakening method can be used to enhance the output power in the speed over 7200 rpm.

VI. CONCLUSION

A new RAFM with SMC cores and ferrite magnet is proposed in this paper. Since the RAFM has the extended stator axial tooth tip and stator radial tooth tip, it can use both the axial PM and radial PM to produce the PM flux linkage. Thus, it can have higher torque ability than the AFM with the extended stator tooth tip in the radial and circumferential direction. As the PMs are surface mounted on the rotor, its manufacturing is very easy. By using the rotational core loss calculation method, it can be found that the majority of the core loss in the stator middle tooth is the alternating one but on the other parts is the rotational one. From anexample discussion, it can be found that the RAFM is a good candidate for the micro electric vehicle application for its high torque ability and low cost.

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